

Cellulose from sunlight

Ideas now being explored for using photosynthesis far more efficiently than at present include "ocean food and energy farms" and "energy plantations planted with BTu bushes"

Graham Chedd

Professor John Heslop-Harrison's recent call (*New Scientist*, vol 65, p 226) for a "cellulose economy" has been anticipated by a number of research projects in the United States aimed at utilising photosynthesis as a means of trapping and storing solar energy. The recent New York meeting of the American Association for the Advancement of Science saw several of the projects pulled together in a symposium entitled "Biochemical and Photosynthetic Aspects of Energy Conversion". The schemes discussed ranged from the already practicable to the distantly glimpsed. They had in common the intention of shortcircuiting the long wait between falling sunlight and useful fuel that accompanies our present industrial use of solar energy in the form of coal and oil.

Agriculture is the only industry that uses today's incident solar radiation. But even agriculture, at least as it is practised in the West, relies on a heavy investment of fossil fuel to harvest the sunlight efficiently. Indeed, it is the generally low efficiency of photo-

synthesis in turning solar energy into chemical energy that is the biggest problem behind the otherwise appealing idea of utilising plants as a major energy source. James Bassham of the Laboratory of Chemical Biodynamics, Lawrence Berkeley Laboratory, pointed out that photosynthesis produces some 155 billion tons dry weight of organic matter, largely cellulose, each year; but that the efficiency of conversion of total solar irradiance into cellulose is commonly around a few tenths of one per cent. This means that large acreages would have to be planted as an energy crop—which immediately raises the question of where the land is to come from at a time when every plantable square inch of the world should be given over to raising food crops.

One possible way out of the impasse is to find a plant with a much higher conversion efficiency. Bassham discussed the so-called C-4 plants such as sugar cane and sorghum, which under optimal conditions have reached conversion efficiencies approaching 3 per cent.

Ordinary plants fix carbon via the Calvin cycle, by which carbon dioxide is reduced to sugars. The rate of this reaction is limited by the supply of carbon dioxide to the plant's chloroplasts; even when plenty of sunlight, water and nutrients are available, the amount of carbon fixed is limited to the rate of supply of carbon dioxide. C-4 plants possess a chemical pump, which keep the chloroplasts primed with carbon dioxide, and so allow a more effective utilisation of the high sunlight intensities of the tropics. But Bassham pointed out that even non-C-4 plants can reach higher conversion efficiencies if the atmosphere in which they grow is enriched with carbon dioxide, to a level of say 0.2 per cent from the normal 0.03 per cent. (This technique has already been used for some years for high value greenhouse produce.)

Bassham envisaged large closed-cycle plastic greenhouses in the deserts of the US South-West as one possible solution to economic cellulose farming. These greenhouses, using recycled water and a CO₂-enriched atmosphere, might be used to raise a crop such as alfalfa. US Department of Agriculture scientists have already developed methods for extracting protein from alfalfa leaves in a form suitable for human nutrition. The present process does not extract all the protein, and the residue is used as a cattle feed. Bassham foresaw technological developments that might allow the extraction of virtually all the protein from alfalfa, leaving a cellulosic fibre. Suppose, he argued, that with the aid of a CO₂-enriched atmosphere such a crop could be boosted to yield 40 tons dry weight per acre per year. Suppose too that from this 10 tons of vegetable protein and 25 tons of cellulose and sugars could be recovered. At one dollar a pound the protein would be worth \$20 000—an order of magnitude less than that considered economic for greenhouse crop production at the moment, but that might change. The amount of sunlight fixed as cellulose and sugars would be around the 1.5 per cent level, a respectable figure. Bassham can see the flaws in his proposal (a little energy input-output analysis might, one suspects, destroy it altogether) but it has the virtues of producing cellulose alongside a valuable food product—without competing for present agricultural lands.

Energy plantations

A more straightforward if brute-force solution to the problems of energy farming was proposed by Clinton Kemp of Inter-Technology Corporation. He listed the requirements of a new major energy source. It should be: capable of storing energy for use at will; high in thermodynamic availability; forever renewable; ecologically inoffensive; widely available in the United States; dependent on existing technology; operable on a large scale in a decade or two; "tolerably" priced; and free of horrendous hazard potential. His solution: Energy Plantations planted with BTu Bushes.

Kemp has done rough energy input-output and cost analyses for his proposal, and came up with some intriguing figures. For instance,

if maize were raised for energy instead of animal feed the costs would be comparable to those presently paid for fossil fuels in the US. If forest conifers were used, planted at some 6000 trees per acre and harvested about once every 12 years the costs would be roughly doubled, because of slower growth rates and very large inventories, to around \$3.00 per million Btu of useful fuel. But perennials have one invaluable advantage over annuals: they can be harvested throughout the year in response to demand, avoiding the huge storage problems of an energy crop that could be harvested only with the seasons. So Kemp and Inter-Technology Corporation have turned in their search for suitable Btu Bushes to fast-growing deciduous trees which re-sprout from the stump when cut, avoiding the need for re-planting every year.

Hybrid poplars

In experimental plots on abandoned farmland in central Pennsylvania they have been growing hybrid poplars from a number of promising clonal lines. One hybrid (Clone 388) planted at some 3700 trees per acre and producing about six or eight harvests per planting, has costs in the range \$1.25 to \$11.45 per million Btu (as compared with oil's present cost of \$1.97 per million Btu and coal's \$1.31 per mBtu). Such a plantation could produce around 120 mBtu per acre per year, at a conversion efficiency of 0.6 per cent. It would grow on marginal land. Some 30 000 acres would be needed to fuel a medium sized 400 MWe power plant; "as a matter of fact", according to Kemp, "to supply the fuel from Energy Plantations for all the generating capacity presently installed (in the US) would require less than 160 million acres even at the rate of conversion of solar radiation to fuel value as low as 0.4 per cent". This average is less than a third of what Inter-Technology estimates is available for Energy Plantations. "We are only at the foot of the learning curve", according to Kemp. "If we could get to a 1 per cent efficiency, we could be exporting the stuff".

One method Kemp considers for utilising the energy stored in his Btu Bushes is to convert it to methane via anaerobic digestion. The development of a "methane economy" based on the anaerobic digestion of plant matter has been urged by Donald Klass, assistant research director of the Institute of Gas Technology; and while Klass was not a speaker at the AAAS symposium, his ideas are clearly gaining support. For example, William Oswald of the Civil Engineering Department at the University of California, Berkeley, discussed his experiments on the digestion of algae grown on sewage stabilisation ponds. His project began by accident, when nutrient-rich stabilisation ponds built to protect the Napa river in California developed dense algal blooms. Oswald is presently testing several easily harvested varieties of algae to see if they will grow on fresh sewage and digest efficiently to produce methane.

A project somewhere between Oswald's and Kemp's in concept but rivalling Kemp's

for audacity is presently being tested by, of all people, the US Navy, at the Naval Undersea Center, San Diego. This is the Ocean Food and Energy Farm, discussed at the AAAS symposium by Howard Wilcox. Wilcox plans to solve the land-shortage problem by going to sea, there to grow on underwater rafts macroalgae-seaweed supplied with nutrients not by sewage but by deep, cold, nutrient-rich water brought to the surface by artificially induced upwellings. Seaweed contains little cellulose, but could be processed by chemical or bacterial action to produce methane plus other products such as fertiliser, ethanol, lubricants, waxes, plastics, fibres—indeed, a complete spectrum of petrochemical-type products. Furthermore, the seaweed could also be used, directly or indirectly, as a food source.

The Navy has already installed at 7-acre experimental underwater farm of kelp, one of the world's fastest growing plants, in about 300 ft of water just off San Clemente Island (Figure 1). California already has a well-developed kelp industry based on natural kelp beds, and based on this experience and their own from the experimental farm Wilcox and his colleagues have begun food production and fuel conversion experiments. From these small beginnings, Wilcox can envisage a dramatic future:

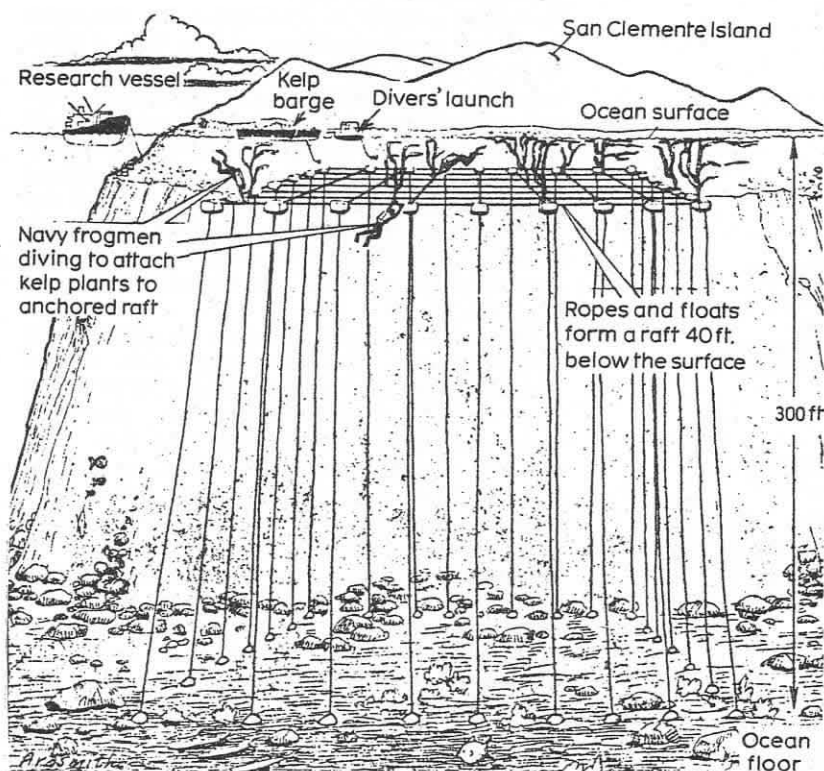
"Assuming a 2 per cent conversion efficiency for converting solar radiation into the stored energy of seaweed compounds, 5 per cent conversion efficiency for the production of human food from the seaweed, and 50 per cent conversion efficiency for the production of other products from the seaweed, the marine farm is conservatively projected to

yield enough food to feed 3000 to 5000 persons per square mile of ocean area which is cultivated, and at the same time to yield enough energy and other products to support more than 300 persons at today's US per capita consumption levels, or more than 1000 to 2000 persons at today's *world average* per capita consumption levels. Since the oceans, conservatively estimated, appear to contain some 80 to 100 million square miles of arable surface water, this means that marine farms could conceivably support a human population ranging from 20 to more than 200 billion persons, depending on the degree of affluence assumed."

A rather more immediately practical source of methane is urban solid waste. D. L. Wise of Dynatech, a Cambridge, Massachusetts, research and development company, presented results of an engineering analysis of a plant processing 1000 tons of waste a day and serving a metropolitan population of about 500 000 people. Gas would be produced by anaerobic digestion from this approximately 280 tons of organic material 1000 tons of waste would contain. The computer analysis finishes up with a price for the gas of almost \$6.00 per million cubic feet—more than twice the current cost. But if the analysis includes credits for the waste disposal, the usable sewage sludge and the scrap iron the process would recover, the cost of the gas drops sharply to a little over \$2.00 per MCF. The final price takes into account the plant's own energy consumption, of roughly 37 per cent of the gas produced. As Wise pointed out, "such a system may be a 100 per cent solution to the solid waste problem, but it would contribute only about 5 per cent to the annual US production of natural gas". On the other hand, 5 per cent is 5 per cent; and in states like Massachusetts, on the end of the natural gas pipelines, the percentage of annual gas consumption capable of being generated from solid waste reaches about 28 per cent. Not surprisingly, Dynatech's analysis is receiving a great deal of attention from US municipalities already struggling hard to solve their solid waste disposal problems.

Glucose from cellulose

Perhaps the most striking presentation in the AAAS symposium, both for its promise and its practicability, was also superficially the most bizarre. The key to the research of Leo Spano and his colleagues at the US Army Natick Laboratories in Massachusetts is a fungus first isolated from a rotting cotton cartridge belt in the jungles of New Guinea in the closing weeks of the second world war. The Army's Natick labs have responsibility for all the consumables used by the US Army and Airforce, and one of the problems they have studied over the years is the protection of clothing from rot. In the last 30 years, the labs have collected some 13 000 microorganisms that can live on cellulose by producing cellulases, enzymes capable of breaking the cellulose polymer back into the glucose from where the original plant constructed it. These enzymes are usually secreted by the microorganisms into their environment.



Marine energy farm. Drawing by Russell Arasmith.
Used by permission of the Los Angeles Times

When, in 1971, the Natick labs were given the task of doing something about the mounting waste disposal problems on US Army bases, someone remembered their star cellulase-producing microorganism, the fungus from the cotton belt, *Trichoderma viride*. *Trichoderma*'s special trick is to produce a cellulase rich in a component capable of breaking down crystalline and generally insoluble cellulose. (Most commercially produced cellulases are obtained from *Aspergillus niger*, which has only a trace of the so-called C_1 enzyme.) Spano and his colleagues derived from the original *Trichoderma* strain mutants that produce two to four times as much cellulase as the wild type, and believe they have not yet reached the upper limit.

The process developed at Natick is simplicity itself. The *Trichoderma* is grown in a culture medium containing spruce pulp and nutrient salts. The culture is then filtered and the solids discarded, leaving a clear straw-coloured enzyme solution with a marked resemblance to American beer. The cellulose solution and milled newspapers are then placed together in a reaction vessel at atmospheric pressure and 50°C. The product is crude glucose syrup; the unreacted cellulose and enzyme are recycled. The yield of glucose is about 50 per cent of the original cellulose. It can be used in chemical, or microbial fermentation, processes to produce chemical feedstocks, single cell proteins, solvents or fuels like ethanol (Figure 2).

Spano and his colleagues have tested their process for a variety of cellulose sources—mostly waste-paper—pretreated in a variety of ways. Amongst the most suitable, Spano

was delighted to recount, were Pentagon documents, which went through the process in a way "you just wouldn't believe", producing pure sugar in just a few hours of digestion. About to come into operation at Natick is a full-scale pilot plant with a capacity of up to 1000 lb of cellulose per month and capable of being stretched to a throughput of some 4000 lb. The Army process is receiving a great deal of attention, both nationally and internationally. Several large chemical companies are seriously considering the production of ethanol by the fermentation of glucose—the way it used to be done, before ethanol was made from oil—and are acknowledging Natick's lead in the production of glucose from cellulose.

Almost all proposals for the utilisation of photosynthesis in the production of usable fuels—be the eventual product methane or ethanol—start with the reduced carbon products made in the plant. Melvin Calvin, after whom the chemical cycle in which the carbon is reduced is named, has for several years championed an alternative: intervene in the energy capture step of photosynthesis and tap off the energy directly, either as electricity or hydrogen. Calvin and his group are working on these ideas at Berkeley (see *Science*, vol 184, p 375).

Storing electrons

Another team interested in the production of hydrogen from the biophotolysis of water is led by Donald Krampitz at Case Western Reserve University, Cleveland, Ohio. Krampitz told the AAAS symposium of his group's work to find a chemical that will "store" the electrons produced in the first stages of photosynthesis so that they can then be used to reduce protons to free hydrogen. Krampitz has been experimenting with a dye, methyl viologen, in a system combining the photosynthetic apparatus from a blue-green alga and a hydrogenase preparation (to catalyse the reduction of protons to hydrogen) from *Escherichia coli*. Light shone on the system produces hydrogen, at least proving that the biophotolysis of water is possible. Krampitz believes that "a goal of 10 per cent conversion of photosynthetic energy into hydrogen is attainable."

One of the major arguments against the widescale use of solar energy has always been that the sun doesn't always shine when you need it; that its energy has somehow to be stored. A corollary has been that what we are running out of is clean liquid and gaseous fuels rather than energy per se, and that you will never be able to power a car by solar energy. Using photosynthesis to turn sunlight into cellulose, and subsequently other enzymatic reactions to turn the cellulose into methane or alcohol, solves both these problems while not bringing in its wake any obvious environmental penalties. It could also relieve the strain on hydrocarbons as a source of petrochemicals. And the appropriation of photosynthesis to produce hydrogen directly at efficiencies approaching 10 per cent could have truly startling consequences for the world's energy supply.

